APPENDIX 9.F — BROKEN-BACK CULVERTS

9.F.1 INTRODUCTION

Sections 9.F.2 "Broken-Back Culvert Guidelines" and 9.F.3 "Broken-Back Culvert Design Procedure" have been taken from the *TxDOT Hydraulic Design Manual*, 2000, which is available at http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd/@Generic__BookView. The Broken Culvert Analysis Program (BCAP) software is available from the Nebraska Department of Roads at http://www.dor.state.ne.us/info/.

9.F.2 BROKEN-BACK CULVERT GUIDELINES

One potential mechanism for creating a hydraulic jump is the broken-back configuration, two types of which are depicted in Figure 9.F-1 and Figure 9.F-2. When used appropriately, a broken-back culvert configuration can influence and contain a hydraulic jump. However, there must be sufficient tailwater, and there should be sufficient friction and length in Unit 3 (see Figure 9.F-1 and Figure 9.F-2) of the culvert. In ordinary circumstances for broken-back culverts, the designer may need to employ one or more devices, such as roughness baffles, to create a tailwater that is high enough to force a hydraulic jump.
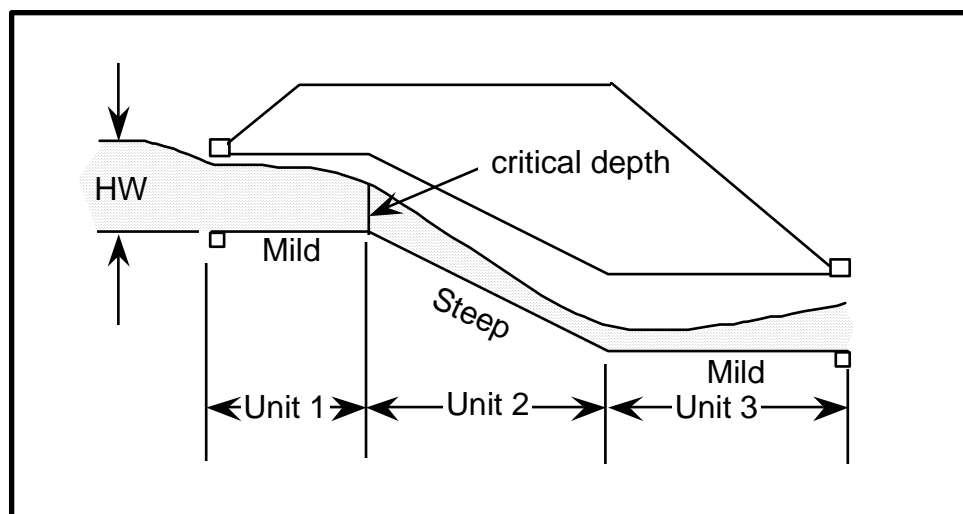

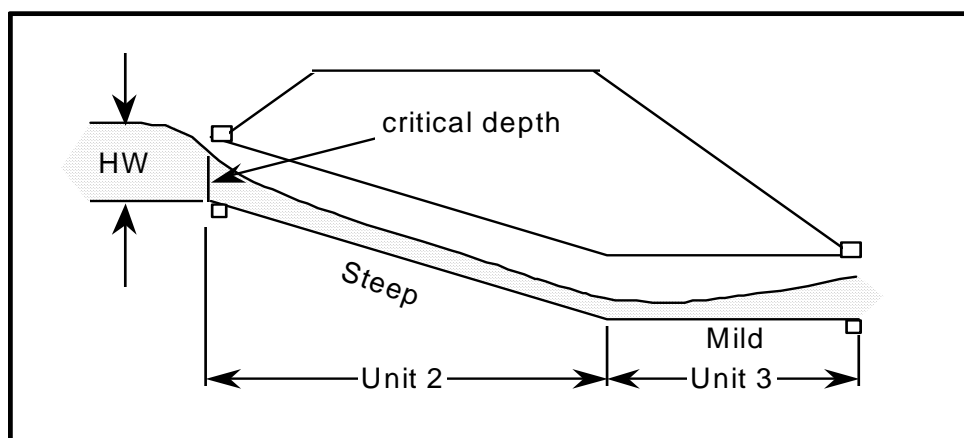**FIGURE 9.F-1 — Three-Unit Broken-Back Culvert**

FIGURE 9.F-2 — Two-Unit Broken-back Culvert

9.F.3 BROKEN-BACK DESIGN PROCEDURE

The design of a broken-back culvert is not particularly difficult, but certain provisions must be made or circumstances found so that the primary intent of reducing velocity at the outlet is realized. Table 9.F-1 outlines the design and provisions procedure of the necessary circumstances.

TABLE 9.F-1 ⎯ Broken-Back Design and Provisions Procedure

Step	Action
Step 1	Establish a flow-line profile.
Step 2	Size the culvert.
Step 3	Begin to calculate a supercritical profile.
Step 4	Complete profile calculations.
Step 5	Consider hydraulic jump cautions.

Step 1   With design discharge and an associated tailwater, establish the flow-line profile using the following considerations:

- With reference to Figure 9.F-1 and Figure 9.F-2, Unit 3 should be long enough to ensure that the hydraulic jump occurs within the culvert.

- For a given total drop, the resulting length of Unit 2 is short, but this may cause the slope of Unit 2 to be very steep.

- Provided that Unit 1 is on a mild slope, its length has no effect on the outlet velocity of any downstream hydraulic function. It is recommended that Unit 1 either not be used or be very short; the result is additional latitude for adjustment in the profiles of Units 2 and 3.

- A longer Unit 3 and a milder (but still steep) slope in Unit 2 together enhance the possibility of realizing a hydraulic jump within the culvert. However, these two conditions are contradictory and usually not feasible for a given culvert location. The designer must make some compromise between the length of Unit 3 and the slope of Unit 2. Unit 3 must be on a mild slope ($d_n > d_c$). It is recommended that this slope be no greater than necessary to prevent ponding of water in the unit. Do not use an adverse (negative) slope.

Step 2   Size the culvert initially according to the directions outlined in Section 9.6 "Design Procedure":

- If a Unit 1 is used, the headwater will most likely result from the backwater effect of critical depth between Units 1 and 2.

- If a Unit 1 is not used, the headwater will most likely result from inlet control.

Step 3   Starting at the upstream end of Unit 2, calculate a supercritical profile, beginning at critical depth and working downstream through Unit 3.

The <u>Direct Step Backwater Method</u> is appropriate. Note the following:

- Critical depth will not change from one unit to the next, but uniform depth will vary with the slope of the unit.

- The increment, δd, should be such that the change in adjacent velocities is not more than 10%.

- The depth in Unit 2 should tend to decrease towards uniform depth, so δd should be negative. The resulting profile is termed an S2 curve.

- Also, δd should be small enough when approaching Unit 3 that the cumulative length does not far exceed the beginning of Unit 3.

- For hand computations, an acceptable expedient is to omit the profile calculation in Unit 2 and assume that the exit depth from Unit 2 is equal to uniform depth in Unit 2.

Step 4   When Unit 3 is reached, complete the profile computations with the following considerations:

- Because uniform depth is now greater than critical depth (mild slope), and flow depth is lower than critical depth, the flow depth tends to increase towards critical depth. Therefore, in Unit 3, δd should be positive.

- The starting depth for Unit 3 is the calculated depth at the end of Unit 2.

- Reset the cumulative length, ΣL, to zero.

- The resulting water surface profile is termed an M3 curve.

- As the profile is calculated, perform the checks outlined below:

  a. As each depth is calculated along Unit 3, calculate the sequent depth, d_s. For more information, see Section 9.F.4 "Hydraulic Jump in Culverts."

  b. Calculate the elevation of sequent depth (d_s + flow-line elevation) and compare it with the tailwater elevation. Tailwater elevation may be a natural stream flow elevation, or may be produced artificially by installing a sill on the downstream apron between wingwalls (refer to the Sills subsection below). Determine the total vertical dimension of this artificial tailwater by adding the elevation at the top of the sill and the critical depth of design discharge flow over the sill. Base this critical depth on the rectangular section formed by the top of the sill and the two vertical wingwalls. If the elevation of sequent depth is lower than the tailwater elevation, the following apply and the designer should proceed to Step 5:

    - hydraulic jump is likely to occur within the culvert;

- outlet velocity is based on the lower of tailwater depth, TW, and barrel height, D; and

- profile calculations may cease, even though the end of the barrel has not been reached.

c. If the computed profile tends towards critical depth before reaching the end of the culvert, the following apply and the designer should proceed to Step 5:

- hydraulic jump is likely to occur within the culvert;

- outlet depth will be equal to critical depth and outlet velocity is based on critical depth; and

- profile calculations may cease, even though the end of the barrel has not been reached.

d. Compare the cumulative length, ΣL, to Unit 3 length. If $\Sigma L \geq$ length of Unit 3, the following apply:

- hydraulic jump does not form within the length of Unit 3;

- exit depth is the present value of d;

- exit velocity is based on exit depth; and

- the broken-back culvert configuration is ineffective as a velocity control device and should be changed in some manner. Alternatives include rearrangement of the culvert profile, addition of a sill and investigation of another device. If the profile is reconfigured, go back to Step 3. Otherwise, skip Step 5 and seek alternative measures.

Step 5   Consider hydraulic jump cautions.

The hydraulic jump should occur within the culvert for the design conditions. However, it is prudent to consider the following cautions:

- If tailwater is very sensitive to varying downstream conditions, it may be appropriate to check the occurrence of the hydraulic jump based on the lowest tailwater that is likely to occur.

- The hydraulic jump may not occur within the barrel under other flow conditions. It is wise to check the sensitivity of the hydraulic jump to varying flow conditions to help assess the risk of excessive velocities.

- If a sill has been employed to force an artificial tailwater, and the hydraulic jump has formed, the outlet velocity calculated represents the velocity of water as it exits the barrel. However, the velocity at which water re-enters the channel is the crucial velocity. This velocity would be the critical velocity of sill overflow.

9.F.4 HYDRAULIC JUMP IN CULVERTS

The following Subsections cover these aspects of hydraulic jump in culverts:

- cause and effect,
- momentum friction,
- comparison of momentum and specific energy curves, and
- potential occurrence of hydraulic jump.

9.F.4.1 Cause and Effect

For a given discharge in any channel, when water flows at a depth that is less than critical depth (supercritical flow), there is a "sequent" (or "conjugate") depth in subcritical flow such that the forces due to momentum change and hydrostatic pressure are in balance between the respective depths. With a proper configuration, the water flowing at the lower depth in supercritical flow can "jump" abruptly to its sequent depth in subcritical flow. This is called a hydraulic jump. With the abrupt change in flow depth, there is a corresponding change in cross-sectional area of flow and a resulting decrease in average velocity.

9.F.4.2 Momentum Function

The balance of forces is represented using a momentum function, as in Equation 9.F.1:

$$M = \frac{Q^2}{gA} + A\bar{d} \qquad (9.F.1)$$

where: M = momentum function
$\quad\quad\quad Q$ = discharge, ft^3/s
$\quad\quad\quad A$ = section area of flow, ft^2
$\quad\quad\quad \bar{d}$ = distance from water surface to centroid of flow area, ft

The term $A\bar{d}$ represents the first moment of area about the water surface. Assuming no drag forces or frictional forces at the jump, conservation of momentum maintains that the momentum function at the approach depth, M_1, is equal to the momentum function at the sequent depth, M_s.

9.F.4.3 Comparison of Momentum and Specific Energy Curves

Figure 9.F-3 provides a sample plot of depth and momentum function and an associated specific energy plot. By comparing the two curves at a supercritical depth and its sequent depth, it can be seen that the hydraulic jump involves a loss of energy. Also, the momentum function defines critical depth as the point at which minimum momentum is established.
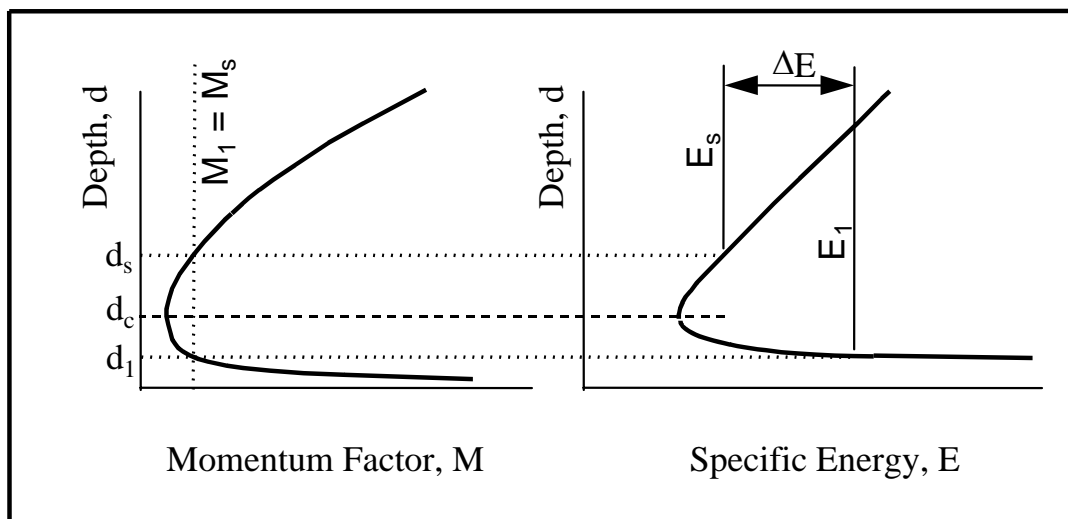
FIGURE 9.F-3 — Momentum Function and Specific Energy

9.F.4.4   Potential Occurrence of Hydraulic Jump

Determine the potential occurrence of the hydraulic jump within the culvert by comparing the outfall conditions with the sequent depth of the supercritical flow depth in the culvert. The conditions under which the hydraulic jump is likely to occur depend on the slope of the conduit.

Under mild slope conditions ($d_c < d_u$) with supercritical flow in the upstream part of the culvert, the following two typical conditions could result in a hydraulic jump:

- the potential backwater profile in the culvert due to the tailwater is higher than the sequent depth computed at any location in the culvert, or
- the supercritical profile reaches critical depth before the culvert outlet.

Under steep slope conditions, the hydraulic jump is likely only when the <u>tailwater</u> is higher than the sequent depth. (See the following three Subsections for more information on sequent depth, and Section 9.F.3, Step 5, for more information on tailwater).

9.F.5   SEQUENT DEPTH

The next Subsections discuss the following sequent depth topics:

- sequent depth for rectangular conduits,
- sequent depth for circular conduits, and
- sequent depth for other shapes.

9.F.5.1   Sequent Depth for Rectangular Conduits

A direct solution for sequent depth, d_s, is possible for free surface flow in a rectangular conduit on a flat slope using Equation 9.F.2. If the slope is greater than approximately 10%, a more complex solution is required to account for the weight component of the water. HEC 14 (Reference *(1)*, Section 9.F.6) provides more detail for such conditions:

$$d_s = 0.5d_1\left(\sqrt{1 + \frac{8v_1^2}{gd_1}} - 1\right) \tag{9.F.2}$$

where: d_s = sequent depth, ft
  d_1 = depth of flow (supercritical), ft
  v_1 = velocity of flow at depth d_1, ft/s

9.F.5.2 Sequent Depth for Rectangular Conduits

A direct solution for sequent depth in a circular conduit is not feasible. However, an iterative solution is possible by following these equations:

- Select a trial sequent depth, d_s, and apply Equation 9.F.3 until the calculated discharge is equal to the design discharge. Equation 9.F.3 is reasonable for slopes up to approximately 10%.

- Calculate the first moments of area for the supercritical depth of flow, d_1, and sequent depth, d_s, using Equation 9.F.3.

- This Equation uses the angle β shown in Figure 9.F.4, which can be calculated by using Equation 9.F.5.

Caution: Some calculators and spreadsheets may give only the principal angle for β in Equation 9.F.5 (i.e., $-\pi/2$ degrees $\leq \beta \leq \pi/2$ degrees).

- Use Equation 9.F.6 to calculate the areas of flow for the supercritical depth of flow and sequent depth:

$$Q^2 = \frac{g\left(A_s\bar{d}_s - A_1\bar{d}_1\right)}{\frac{1}{A_1} - \frac{1}{A_s}} \tag{9.F.3}$$

where: Q = discharge, ft^3/s
  A_s = area of flow at sequent depth, ft^2
  $A_s\bar{d}_s$ = first moment of area about surface at sequent depth, ft^3
  $A_1\bar{d}_1$ = first moment of area about surface at supercritical flow depth, ft^3

$$A\bar{d} = \frac{D^3}{24}\left(3\sin\beta - \sin^3\beta - 3\beta\cos\beta\right) \tag{9.F.4}$$

where: $A\bar{d}$ = first moment of area about water surface, ft^3
  D = conduit diameter, in
  β = angle shown in Figure 9.F-4 and calculated using Equation 9.F.5

$$\beta = \cos^{-1}\left(1 - \frac{2d}{D}\right) \tag{9.F.5}$$

$$A = \frac{D^2}{8}\left[2\cos^{-1}\left(1 - \frac{2d}{D}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d}{D}\right)\right)\right] \tag{9.F.6}$$
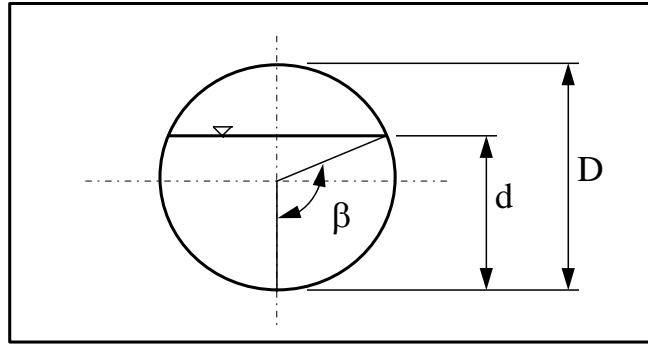
FIGURE 9.F-4 ⎯ Determination of Angle β

9.F.5.3 Sequent Depth for Other Shapes

Equation 9.F.3 is applicable to other conduit shapes having slopes of approximately 10% or less. The first moment of area about the surface, $A\bar{d}$, is dependent on the shape of the conduit and depth of flow. Acquire or derive a relationship between flow depth and first moment of area.

9.F.6 REFERENCES

(1)   Federal Highway Administration, *Hydraulic Design of Energy Dissipators for Culverts and Channels*, Hydraulic Engineering Circular No. 14, FHWA-EPD-86-110, 1983, Revised 1995.